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Progress Report on

Studies of

Water and Climate

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I. Summary of Accomplishments

This research project involves the investigation the vertical profiles of temperature and moisture in convective regimes, using moist available energy as a guide. The results have been used to develop an improved cumulus parameterization. A paper on this parameterization has been completed during this reporting period, and has been accepted for publication in the *Journal of the Atmospheric Sciences* (Wang and Randall 1996). The following is a summary of the paper.

It is well known that cumulus convection, especially deep and intense convection, is one of the major processes affecting the dynamics and energetics of large-scale atmospheric circulations. One of the important effects of cumulus convection on the large-scale thermodynamic structure is to release the convective instability, so as to modify or "adjust" a conditionally unstable atmosphere towards a more stable state which can be called the equilibrium state. This is the basis of the various convective adjustment schemes. The key problems are specification of the equilibrium state and the criterion for activation of convection. These differ from scheme to scheme.

The simplest cumulus parameterizations are the moist convective adjustment (MCA) schemes (Manabe *et al.*, 1965; Miyakoda *et al.*, 1969; Krishnamurti and Moxim, 1971; Kurihara, 1973). In MCA, it is assumed that deep moist convection acts to restore the lapse rate to a saturated moist adiabat, which can be called the "equilibrium state." When the large-scale sounding becomes more unstable than the equilibrium state, and if sufficient moisture is available, the sounding is adjusted toward the equilibrium state. This stabilization is attributed to cumulus convection. The main limitations of MCA are that it does not simulate penetrative convection, and that the equilibrium state is saturated and so not very realistic.

Arakawa and Schubert (1974) developed a sophisticated cumulus parameterization which includes many physical processes. It can be viewed as an adjustment scheme. In the Arakawa-Schubert (AS) parameterization, a spectrum of cloud types is considered, so that the effects of different cloud types can be seen explicitly. Also, the AS parameterization relates convective activity to the large-scale forcing, which involves horizontal and vertical advections, radiation, and the surface fluxes of sensible heat and moisture. In particular, the AS parameterization makes use of the assumption that the real atmosphere is in a quasi-equilibrium state, in which the rate of destabilization by large-scale processes and the rate of stabilization by cumulus convection almost balance each other. That is, the large-scale forcing produces convective clouds, and the clouds consume the instability generated by the large-scale forcing, so that the atmosphere stays close to an equilibrium state in which the conditional instability is weak, or non-existent. In this sense, the AS parameterization is an adjustment scheme.

According to the quasi-equilibrium hypothesis, the rate of instability increase due to large-scale processes is fully and immediately counteracted by convection, so that the atmosphere does not become very unstable. The assumption of such a quasi-equilibrium means that the AS parameterization cannot predict the Convective Available Potential Energy (CAPE) stored in a weather system. Some "relaxed" schemes, in which the exact quasi-equilibrium assumption is not strictly enforced, have been developed to implement the AS parameterization (e.g. Moorthi and Suarez, 1992; Randall and Pan, 1993). These schemes adjust towards the equilibrium state over a finite time scale.

Betts (1986), Betts and Miller (1986) presented a "relaxed" convective adjustment scheme in which, as in the other adjustment schemes, a conditionally unstable sounding is adjusted by convection toward an equilibrium state. They specified the equilibrium temperature sounding to follow a virtual moist adiabat at low levels and a pseudoadiabat at high levels. They specified the equilibrium moisture profile empirically, although in fact it may vary for different regions and synoptic situations. The feedbacks between cumulus clouds on the large-scale environment were not explicitly or "mechanistically" represented, e.g. in terms of mass fluxes.

Since the fundamental physical basis of adjustment methods is that convection acts to release the convective instability (or conditional instability) so as to drive the atmosphere towards a neutral state, a measure of the conditional instability is a key ingredient of such schemes. The conventional methods of measuring conditional instability are not fully satisfactory, however: the effects of environmental return flow are neglected, and the level of origination of the lifted parcel, must be assumed. The Generalized Convective Available Potential Energy (GCAPE) of Randall and Wang (1992) overcomes these restrictions, and therefore is a prior more accurate measure of the conditional instability. Based on Lorenz's (1978, 1979) concept of Moist Available Energy (MAE, Randall and Wang 1992) defined the GCAPE as the "vertical component" of the MAE and used it as a measure of the conditional instability of an atmospheric column. The definition of the GCAPE makes a "reference state," which is the unique state in which the system's enthalpy is minimized; it is also a statically neutral or stable state.The GCAPE is the vertically integrated enthalpy difference between a given state and the corresponding reference state, and represents the total potential energy available for convection in a given sounding.

In this paper, we propose an adjustment scheme based on the concept of GCAPE. The new parameterization combines some elements of the Arakawa-Schubert parameterization and the Betts-Miller parameterization, and tries to correct some limitations of those two parameterizations. The reference state associated with the GCAPE is chosen as the end-state of the adjustment, or the equilibrium state. This equilibrium state is determined by the given state, so that it varies in space and time. We relax towards the equilibrium state (as in the Betts-Miller parameterization), so that no strict quasi-equilibrium between large-scale forcing and convection is imposed.

We are attracted to the idea of using the GCAPE reference state as the equilibrium state of the adjustment because the GCAPE reference state is completely general and is not based on a cloud model. We have to keep in mind, however, that the GCAPE reference state is reached by reversible adiabatic processes. Real convection involves crucially important irreversible processes such as precipitation and mixing. Obviously, a cumulus parameterization has to take these irreversible processes into account.

We take them into account by using a simple cloud model. This means that although we avoid the use of a cloud model in the definition of the equilibrium state, we do use one to determine the convective feedback.

One might argue that an ideal cumulus parameterization would avoid using any cloud model at all. This is the idea behind the Betts-Miller parameterization. It is also the idea behind the empirical cumulus parameterization developed by Liu (1995), who used the logical framework of the AS parameterization, but employed both an empirical equilibrium state (in which an empirically defined measure of CAPE is small) and an empirical formulation for the feedback of the convection on the large-scale fields.

It seems desirable to avoid both empiricism and cloud models as far as possible. The present study aims to show that it is possible to use the concept of GCAPE to define the equilibrium state without using empiricism or cloud models, but we do resort to a cloud model to determine the convective feedback.

There is no contradiction between the use of the idealized reference state which is defined with respect to adiabatic reversible processes and the simultaneous use of a cloud model which includes irreversible processes like mixing and precipitation. Our idea is that the convection "tries" to adjust to the reference state, but that irreversible processes prevent this adjustment from being fully realized.

The incorporation of a cloud model inevitably and regrettably causes our parameterization to fall far short of the power and generality of Lorenz's MAE concept. For example, the cloud model does assume particular levels of origin for the updrafts and downdrafts.

As explained in detail later, we use the predicted (or observed) sounding and the corresponding GCAPE reference state, together with a relaxation time scale (discussed below), to determine the convective tendency of the moist static energy. This is not enough for a cumulus parameterization, however. In a prognostic model we need to know the tendencies of temperature and moisture separately.

In order to find them, we introduce the cloud model mentioned above, the form of the diagnostic model of Nitta (1975), modified to incorporate the downdrafts of Johnson (1976).[1] The convective moist static energy tendency is used as input to the diagnostic model, which determines the corresponding tendencies of temperature and moisture, and also yields the precipitation rate.

A second new aspect of our parameterization is that we relate the adjustment time scale to the large-scale forcing, so that the intensity of cumulus convection is controlled by the large-scale forcing (as in the Arakawa-Schubert parameterization).

A cumulus parameterization for large-scale models has been presented. It is an adjustment

[1] The cloud model used by Nitta is an entraining plume model of the type used in the AS parameterization. Emanuel (1991) has criticized the use of entraining plume models in cumulus parameterizations. Recent work by Lin (1994) suggests, however, that these models can in fact serve as realistic agents of convective transports.

scheme. The reference state associated with the GCAPE is the end-state of the convective adjustment. This reference state varies from case to case, depending on the given soundings. The time scale for the adjustment also varies, ranging from several hours to several tens of hours, depending on the intensity of the large-scale forcing. Because the adjustment time scale is related to the large-scale forcing, the intensity of convective activity is determined by the large-scale forcing as in the Arakawa-Schubert parameterization.The methods of Nitta (1975) and Johnson (1976) are combined to diagnose the convective heating and drying rates.

The closure assumption of the present parameterization can be written as

$$\left(\frac{\partial h}{\partial t}\right)_{CU} = \frac{h_r - h}{\tau_{adj}}. \tag{1}$$

Although (1) looks similar to the closure assumptions of Betts (1986) which are

$$\left(\frac{\partial T}{\partial t}\right)_{CU} = \frac{T_{ref} - T}{\tau_{adj}} \tag{2}$$

and

$$\left(\frac{\partial q}{\partial t}\right)_{CU} = \frac{q_{ref} - q}{\tau_{adj}}, \tag{3}$$

where T is temperature q is total water mixing ratio, and the subscript "ref" denotes the quasi-equilibrium reference state profiles, some important differences exist. One is that we allow τ_{adj} to change from case to case, depending on the large-scale forcing, while Betts and Miller (1986) use a prescribed constant τ_{adj}. In our parameterization, when the large-scale forcing is strong, τ_{adj} is small; and so the effects of convection are strong. On the other hand, when the large-scale forcing is weak or negative, a large τ_{adj} is used, and so convection is inhibited. In this way, the intensities of cloud activity and precipitation are related to the large-scale forcing.

The criterion for activating the Betts-Miller parameterization is that positive buoyancy is encountered when a hypothetical cloud parcel is lifted adiabatically from the boundary layer. However, as it has been shown (Thompson et al., 1979; Wang and Randall, 1994) that in GATE the observed precipitation rate is positively correlated with the intensity of large-scale forcing, but negatively correlated with the CAPE. This means that it may be more realistic to relate the effects of convection to the large-scale forcing than to the amount of CAPE.

Although both the Betts-Miller parameterization and the present parameterization are relaxation schemes, the final reference states are different. Betts (1986) determined the equilibrium state empirically from observed soundings. The equilibrium state of our parameterization is determined by the given soundings and the GCAPE theory, modified to include the effects of detrainment below the neutral buoyancy level.

A key difference between our parameterization and the Arakawa-Schubert (AS) parameterization is in the calculation of the cloud-base mass flux. In the AS parameterization, the quasi-equilibrium assumption is used to calculated the cloud-base mass flux. The quasi-equilibrium assumption requires that, at any moment, the rate of production of CAPE by large-scale forcing is balanced by the consumption of CAPE by convection, so that after each time step the CAPE remains unchanged. A cloud model is used to measure conditional instability and to define the reference state.

In our parameterization, no cloud model is needed to find the reference state. The effects of convection on the moist static energy are obtained from (1). Then, by using Nitta's method, we determine the effects of convection on the temperature and moisture fields. Both the AS parameterization and our parameterization relate the intensity of convection to the large-scale forcing, but in different ways. The present parameterization is a relaxation scheme in which no exact balance is required.

We do not adjust directly to the temperature, moisture, and condensed water of the reference state because this state is highly unrealistic, especially in view of high condensed water contents in the upper troposphere. We have considered the following strategy, however: On a given time step, adjust the temperature, moisture, and condensed water some fraction of the way to the reference state. Then, within the same time step, allow a microphysics parameterization to reduce the condensed water concentration in the upper troposphere by precipitation, and to increase the water vapor content of the lower troposphere by evaporating the falling rain. This approach would still include a "cloud model" in the sense that we would have parameterizations of precipitation, evaporation, and so on. Future work may go in this direction.

We regard this as an exploratory study. Certainly much additional work is needed before the ideas here are ready for application in large-scale models. Nevertheless, we are encouraged by our results to date and feel that this approach merits further investigation.

Publications resulting from this project

Wang, J., and D. A. Randall, 1991: The Moist Available Energy of a Conditionally Unstable Atmosphere. Paper presented at the *19th Conference on Hurricanes and Tropical Meteorology of the American Meteorological Society*, Miami, Florida.

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Wang, J., and D. A. Randall, 1994: A cumulus parameterization based on the concept of GCAPE. Paper presented at the *Tenth Conference on Numerical Weather Prediction of the American Meteorological Society*, Portland Oregon.

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